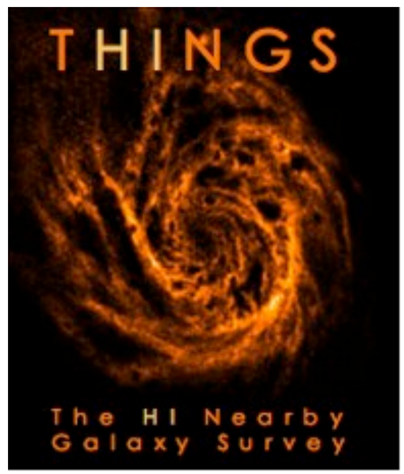
The Star Formation Law at sub-kpc Resolution

From the Inner Disks to the Outskirts of Nearby Galaxies



F. Bigiel (UC Berkeley), A. Leroy, F. Walter (MPIA)
& *THINGS* & HERACLES Teams

Reminder

The Star Formation Law

What is a SF law?

→ A relation connecting Σ_{SFR} to Σ_{gas}: $\Sigma_{SFR} = A \cdot \Sigma_{gas}^{N}$

(going back to Schmidt 1959)

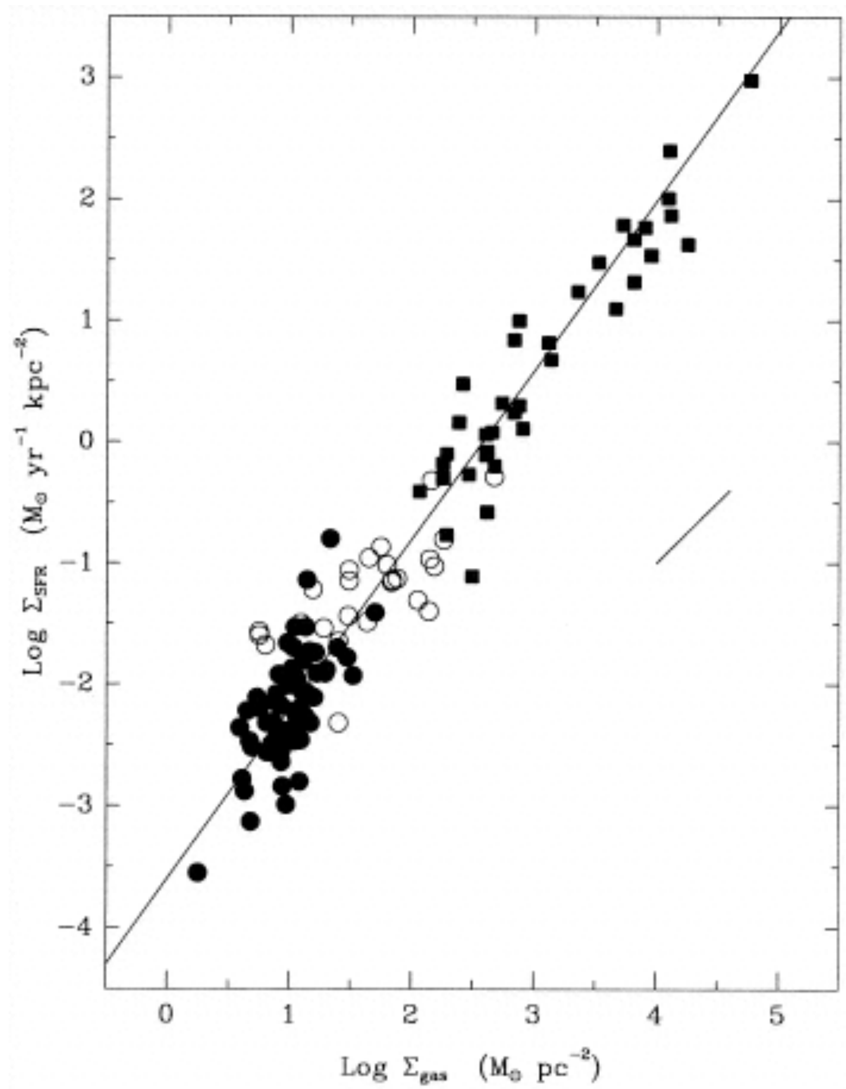
Why SF law?

→
- Derive physical insight into what drives SF (e.g. by comparing empirical relations to predictions from theory)
- SPH modeling of galaxy evolution
- Predictive power: measure the gas (surface) density and estimate the SFR (surface) density

Previous studies include e.g.

- Schmidt (1959): N≈2 (Milky Way)
- Kennicutt (1989,1998): N≈1.4 (sample of ~90 nearby galaxies)
- Wong & Blitz (2002): N=1.2-2.1 (6 nearby spiral galaxies)
- Boissier et al. (2003), Heyer et al. (2004): N≈2 (16 galaxies) and N≈3.3 (M33)

The Kenicutt Plot…



Kennicutt (1998):
Disk-averaged SFR vs. gas surface densities (closed circles)
Starbursts (squares) and the centers of spirals (open circles)

Optical disks - Methodology

The Star Formation Law - Methodology

- Previous studies assessed the SF law by either
    - ➢ averaging emission across the optical disks of galaxies (e.g. Kennicutt 1998)
    - ➢ or by deriving radial profiles (azimuthal averages in tilted rings) (e.g. Wong & Blitz 2002, Boissier et al. 2003, Heyer et al. 2004)

- Most recent studies assess SF locally, using aperture photometry on individual HII regions (e.g. Calzetti et al. 2005, Pérez-González et al. 2006, Kennicutt et al. 2007)

- This study: the spatially resolved SF law **pixel-by-pixel** at 800 pc resolution across the optical disks of 12 nearby spirals

- For this analysis, we need
    - ➢ Gas surface density maps (HI & CO)
    - ➢ SFR surface density maps

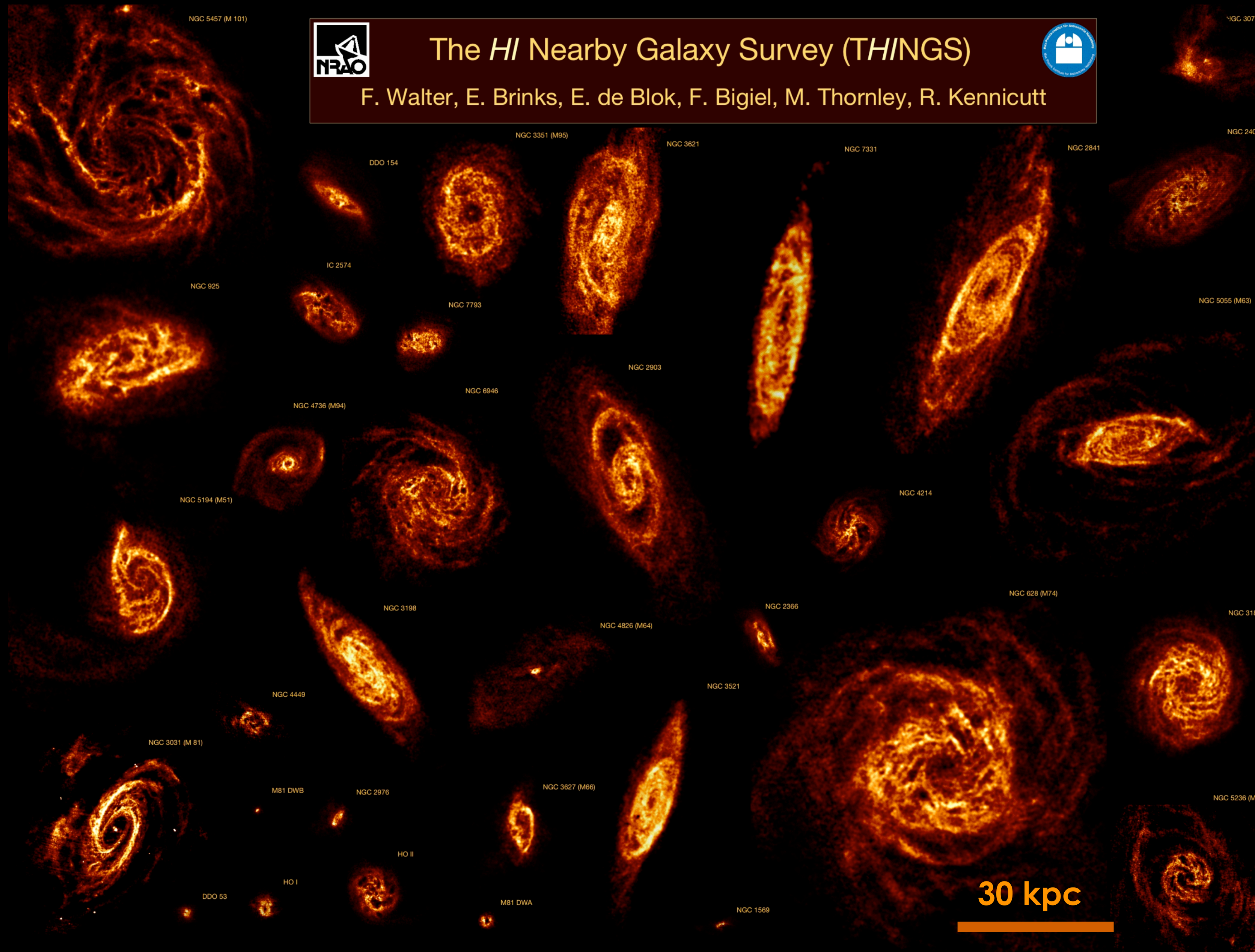
The HI Nearby Galaxy Survey

F. Walter, E. Brinks, E. de Blok,
F. Bigiel, M. Thornley, R. Kennicutt

A Few Things About THINGS

- ~500h of B,C,&D array : Large NRAO VLA program ('03-'06)
- 34 galaxies: Sa - Irr
- Resolution ~ 6" (100-300 pc)
- Velocity Resolution ~ 5 km s^{-1}
- Intensity map sensitivity ~ 5 $\cdot 10^{19}$ cm^{-2} (0.4 $M_{\odot}/pc^{-2}$)
- data: ~ 1 Tbyte
- Targets complement SINGS *Spitzer* Legacy Survey

EveryTHINGS



The HERA CO-Line Extragalactic Survey
HERACLES

A. Leroy, F. Walter, F. Bigiel et al. 2009

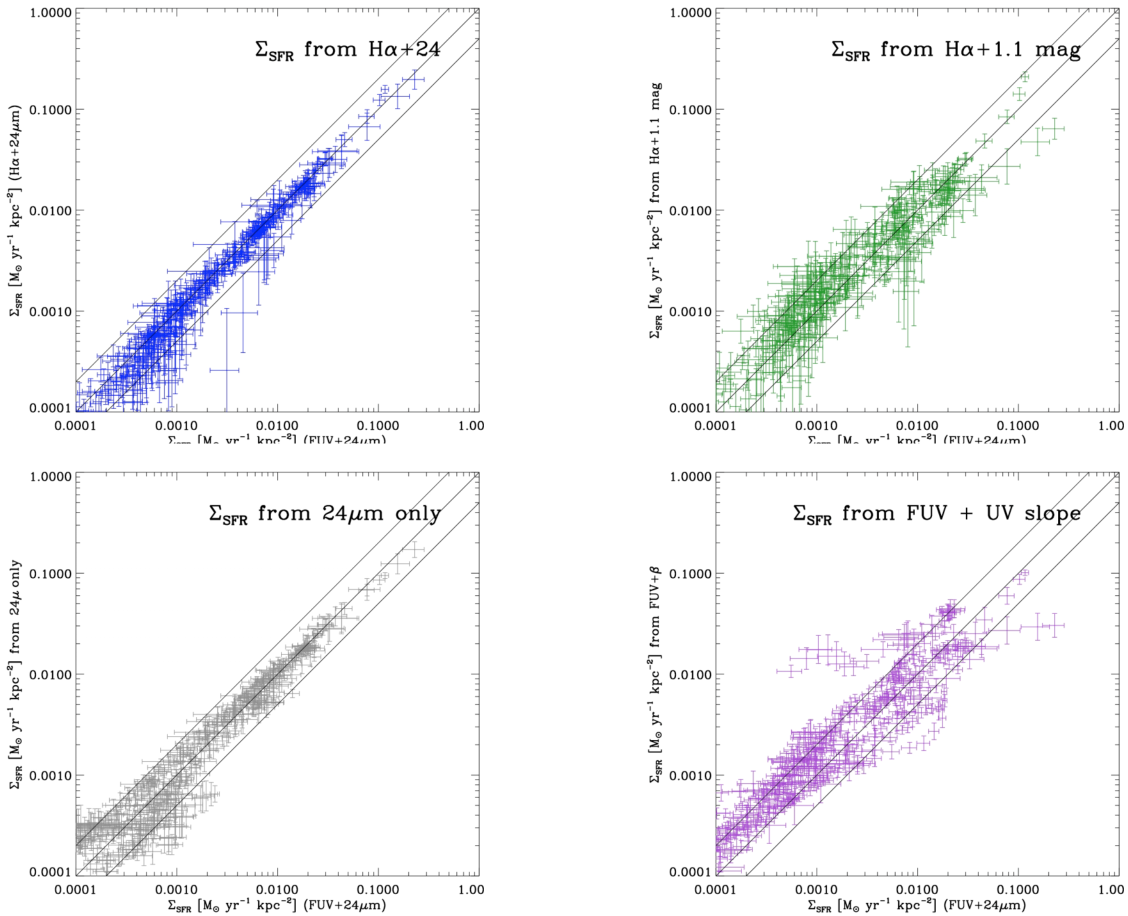
HERACLES

- ~500h with the HERA focal plane array at the IRAM 30m telescope (‘07-’08)
- 44 galaxies: Sa - Irr
- Resolution ~ 11” (300 pc - 1 kpc)
- Velocity Resolution ~ 2.6 km s^{-1}
- Intensity map sensitivity ~ 2 $M_{\odot}/pc^{-2}$
- Extended mapping: Entire optical disk for most galaxies
- Targets complement subsample of THINGS & SINGS *Spitzer* Legacy Survey

Calibrating SFRs

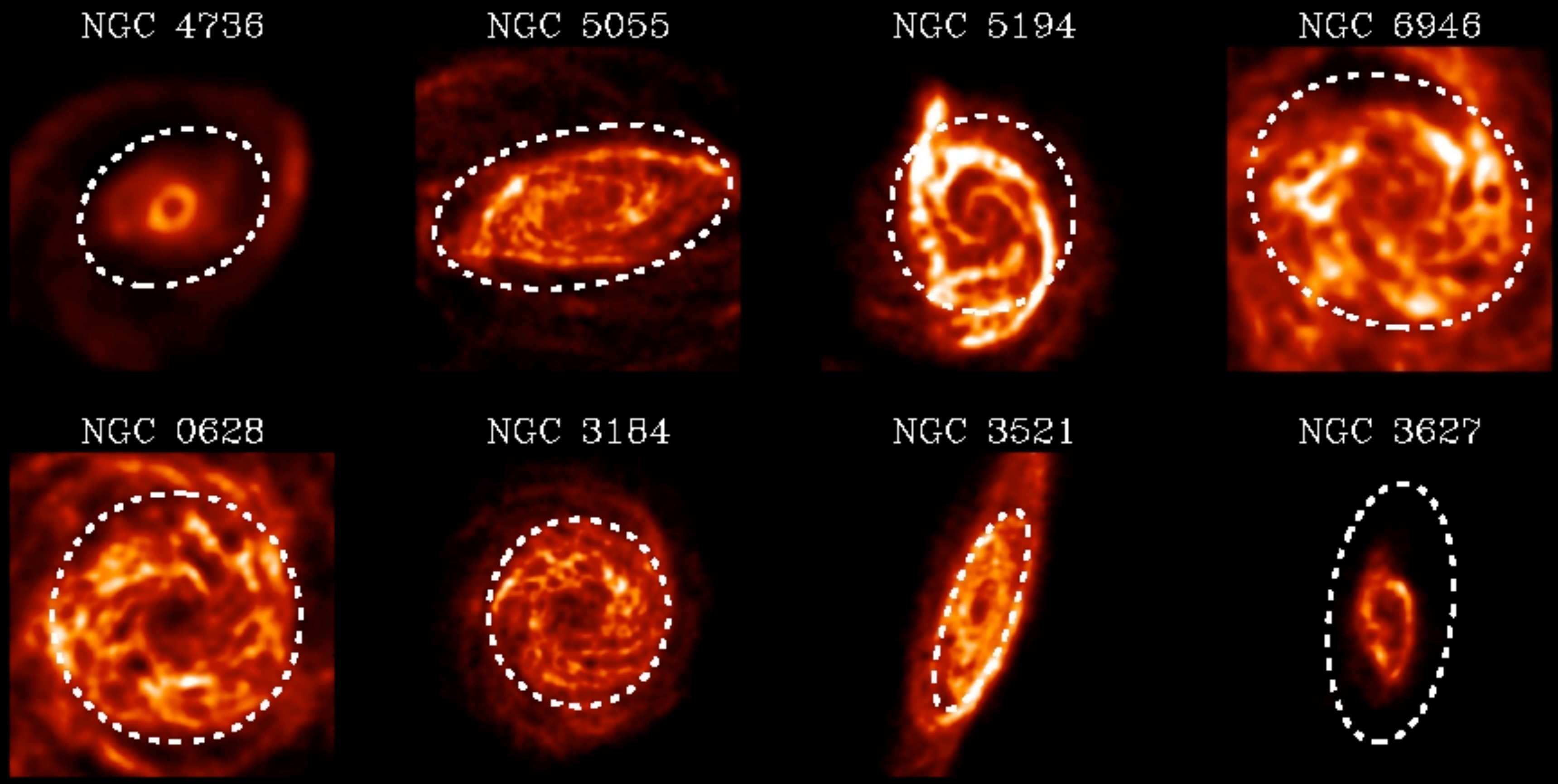
- Combination of FUV (unobscured SF) and 24 μm emission (obscured SF):
  - Following idea in Kennicutt et al. (2005, 2007)
  - Based on Hα + 24 μm calibration by Calzetti et al. (2007)

Σ_{SFR} from other approaches



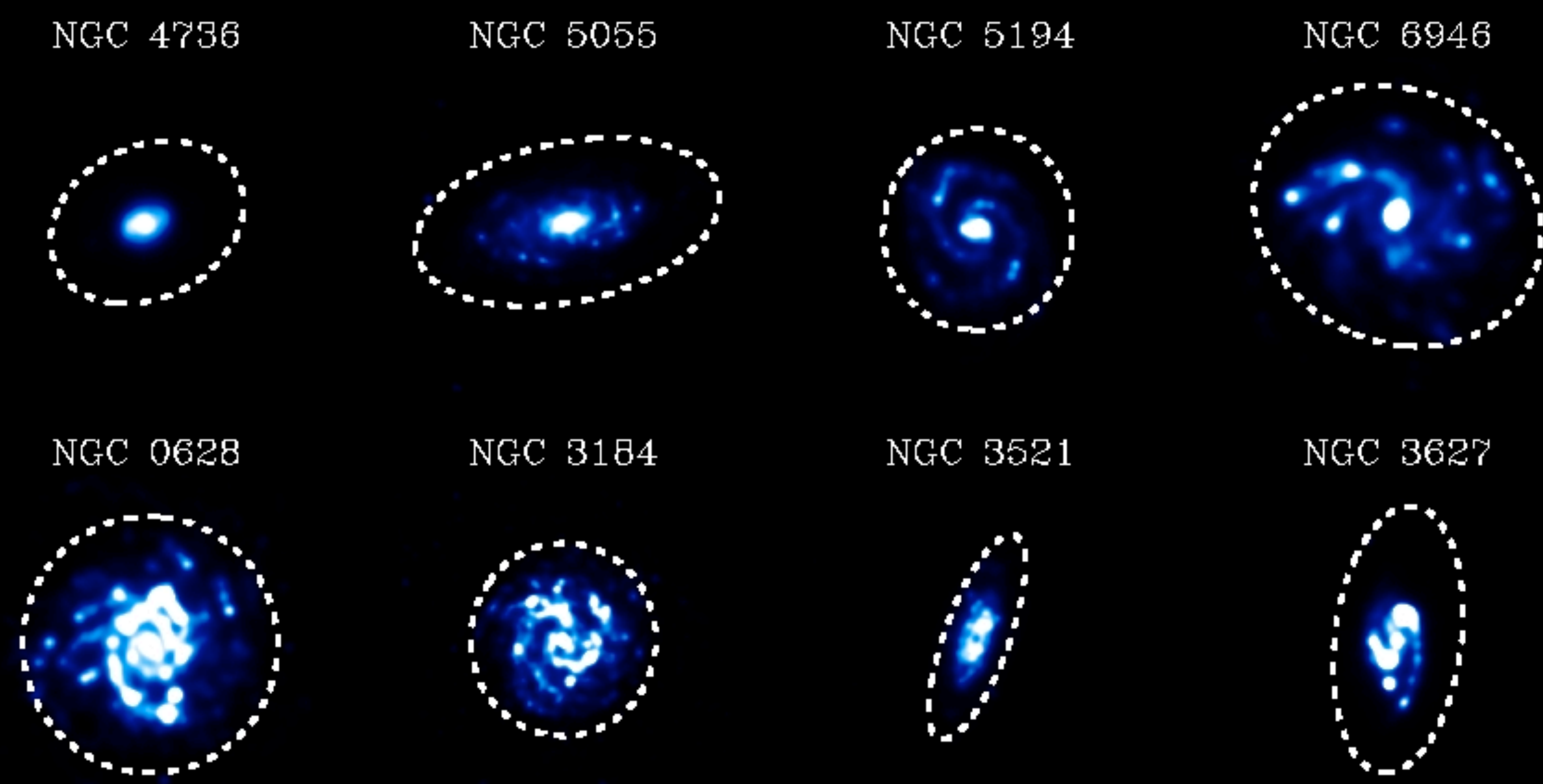
Σ_{SFR} from our FUV + 24μm approach

HI Maps

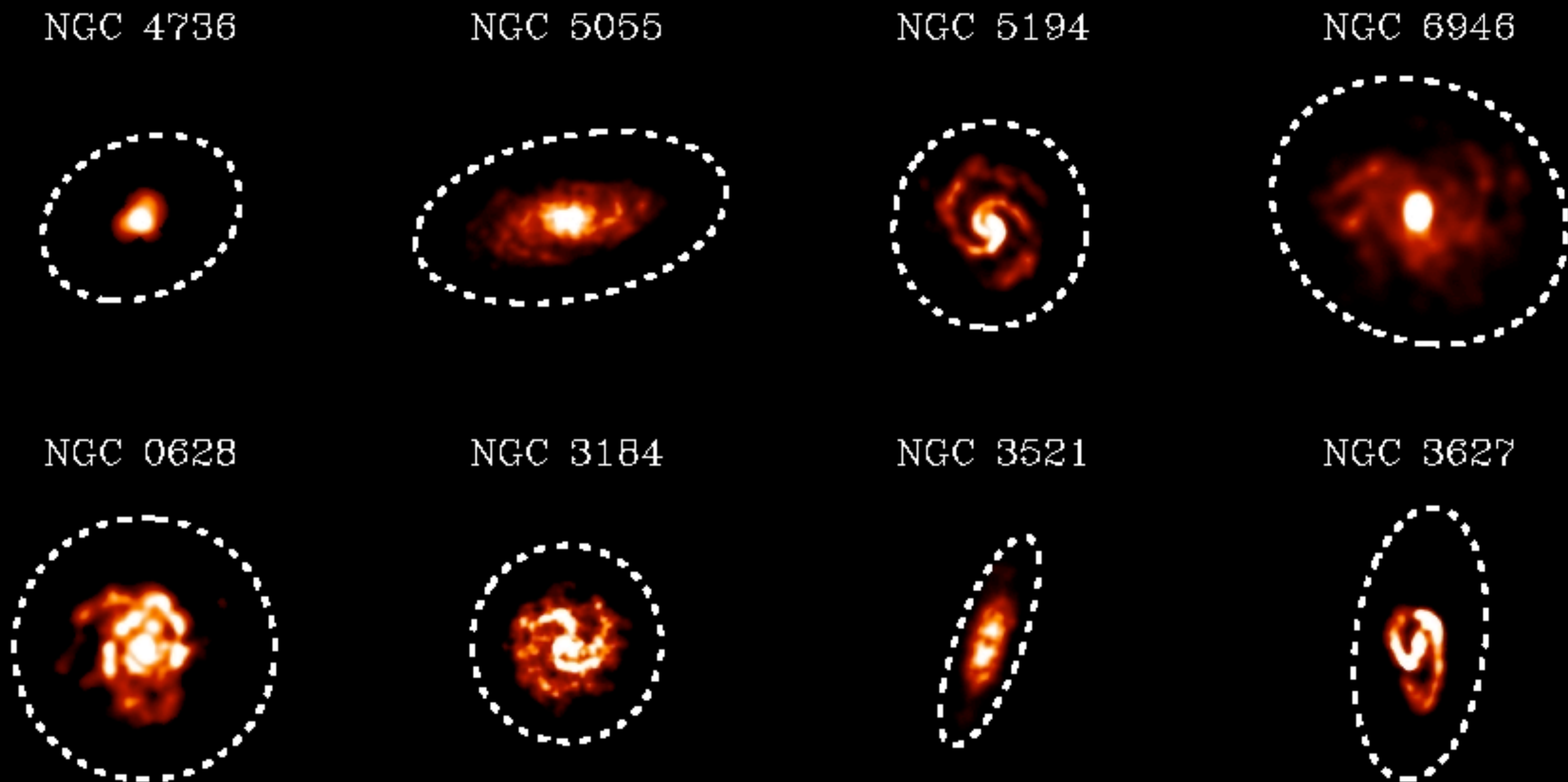


NGC 4736
NGC 5055
NGC 5194
NGC 6946
NGC 0628
NGC 3184
NGC 3521
NGC 3627

SFR Maps

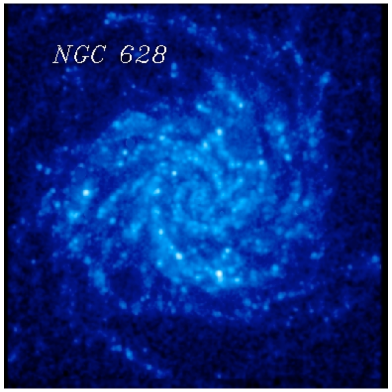

NGC 4736
NGC 5055
NGC 5194
NGC 6946
NGC 0628
NGC 3184
NGC 3521
NGC 3627

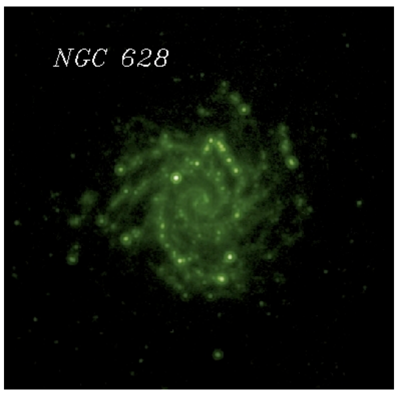
H_2 Maps



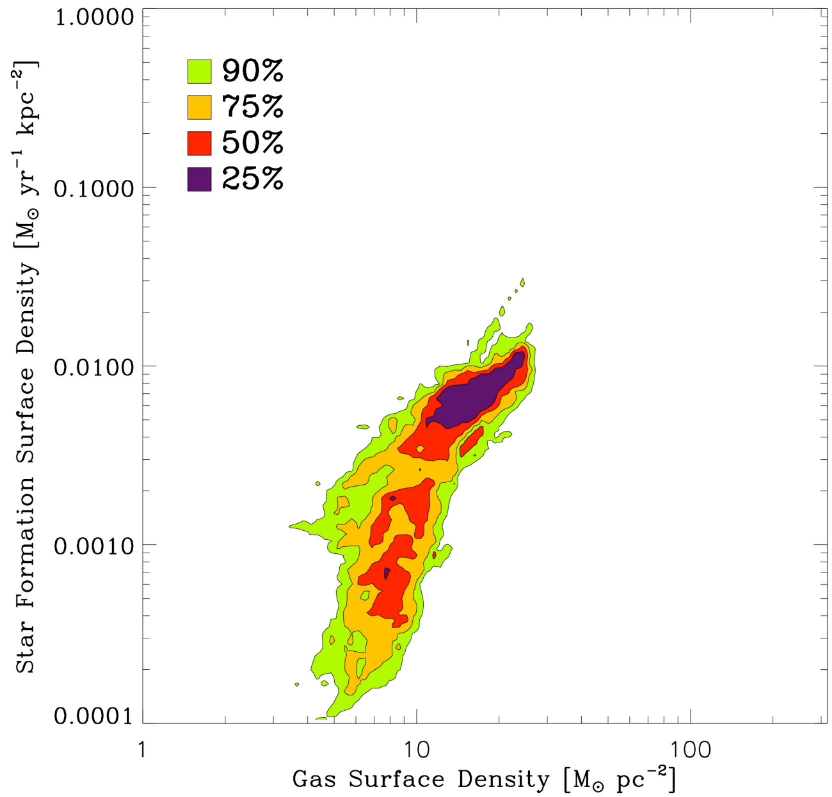
NGC 4736
NGC 5055
NGC 5194
NGC 6946
NGC 0628
NGC 3184
NGC 3521
NGC 3627

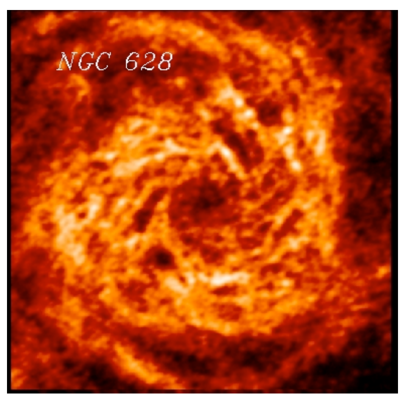
The Basic Plot ...

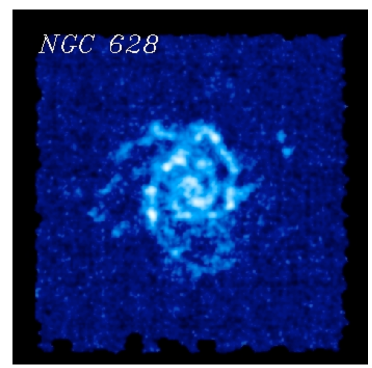




star formation
vs. gas
in M74

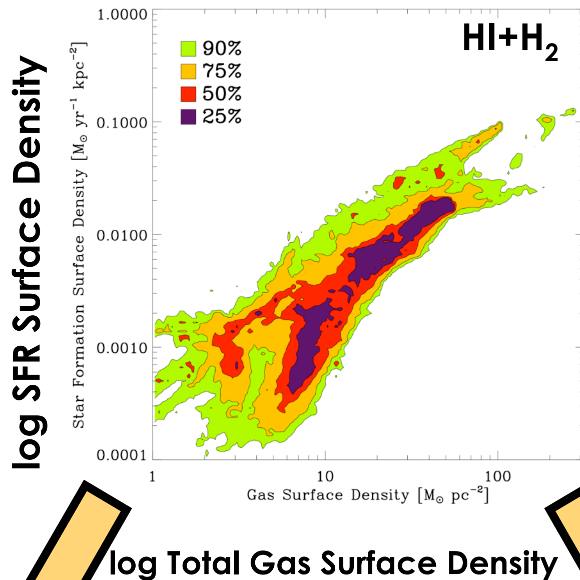






Contours reflect data density of points; equal weight to each radius

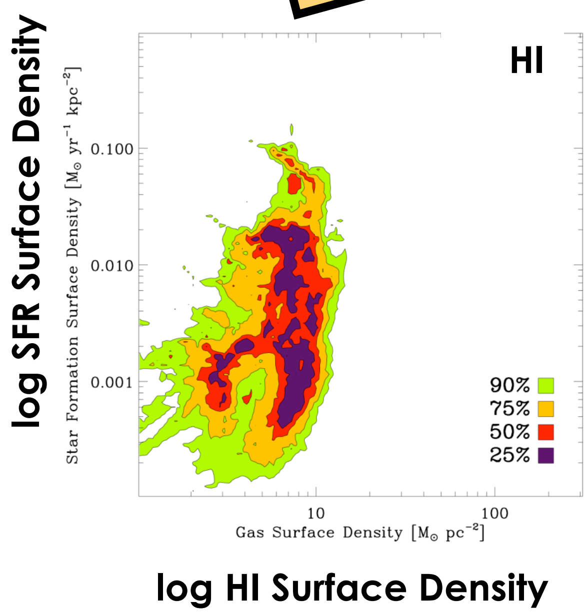
The Combined Plot - 12 Spirals at 800 pc Resolution

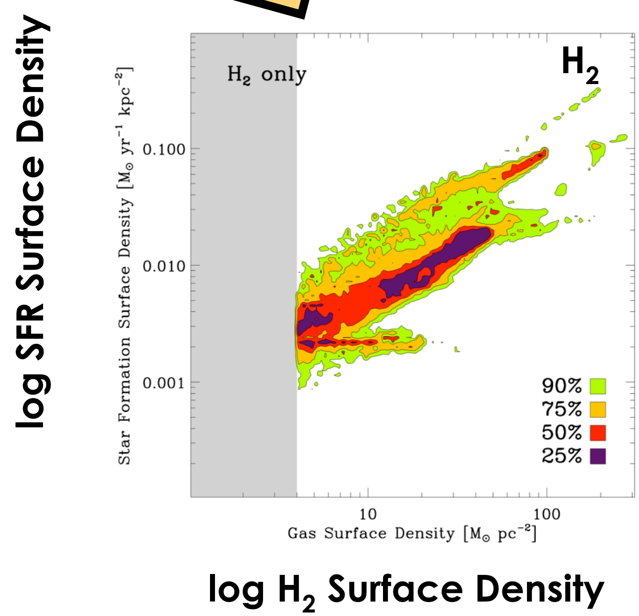


- A saturation of Σ_{HI} at ~ 9 $M_\odot$ pc^{-2}

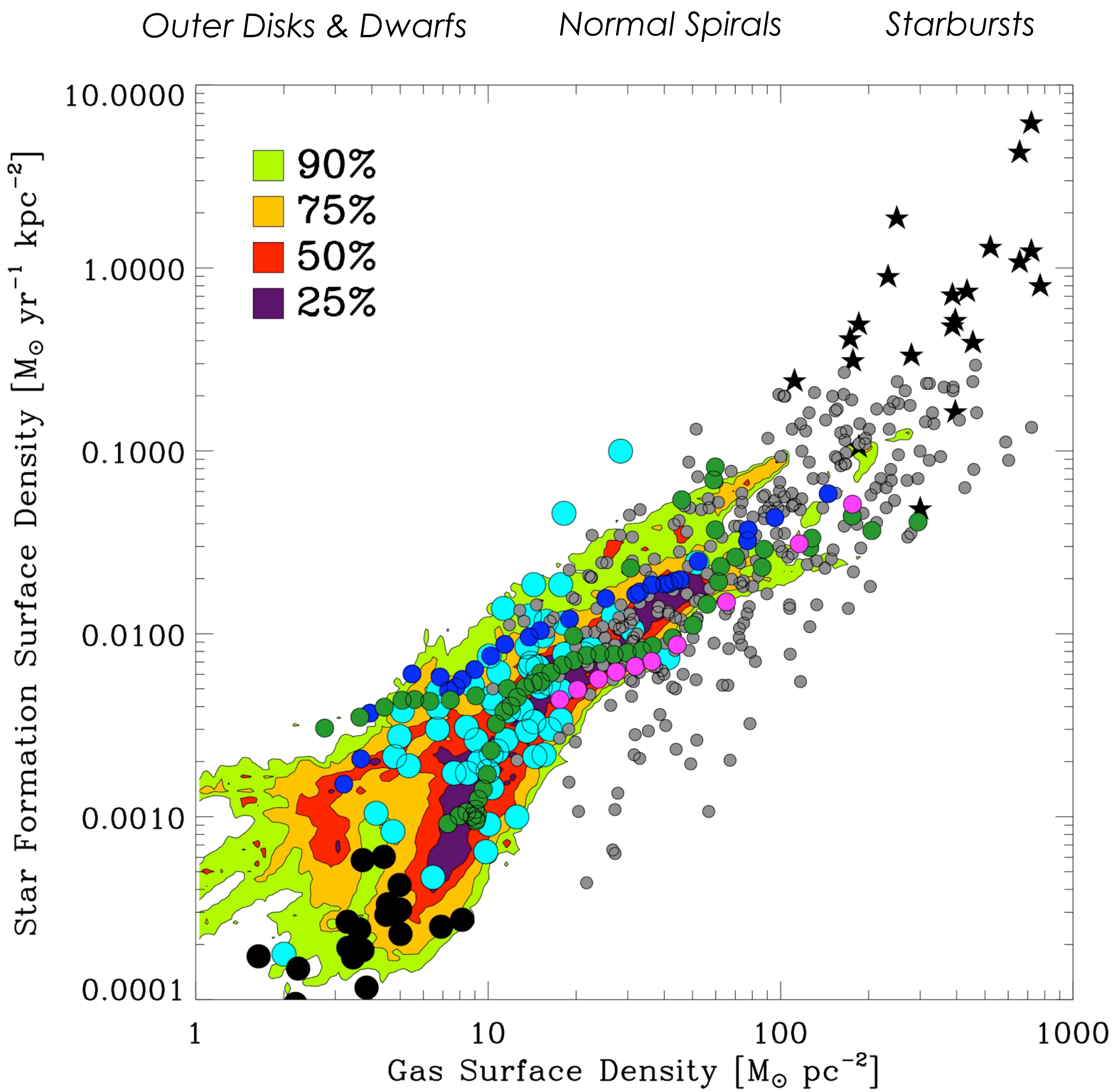
- Σ_{H2} is tightly correlated with Σ_{SFR} ($N_{H2} = 1.0 \pm 0.2$)

- Data are compatible with a **molecular gas** Schmidt Law, showing a constant SFE (τ~2*10^9 yrs)



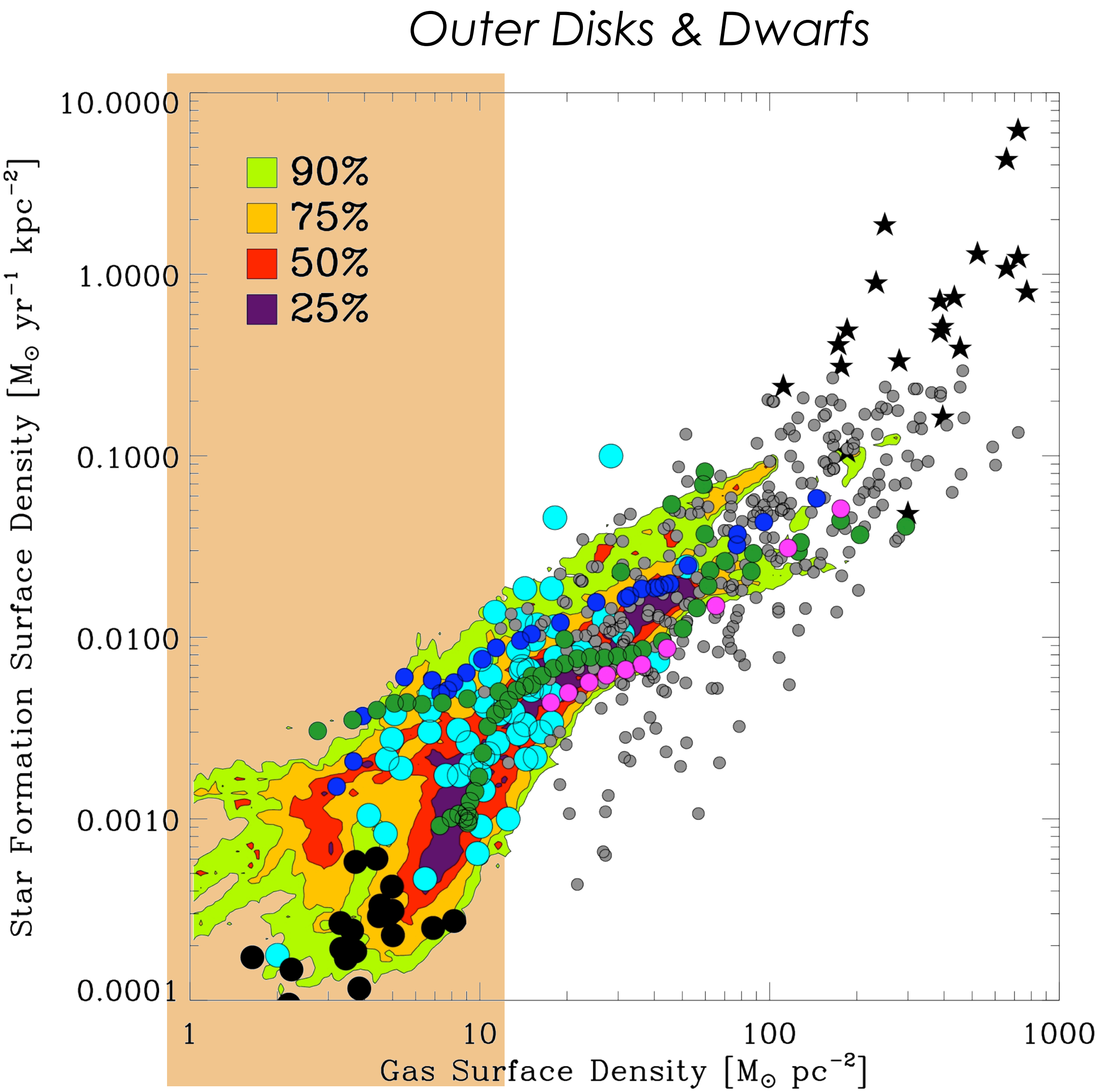


Agreement with Previous Results …



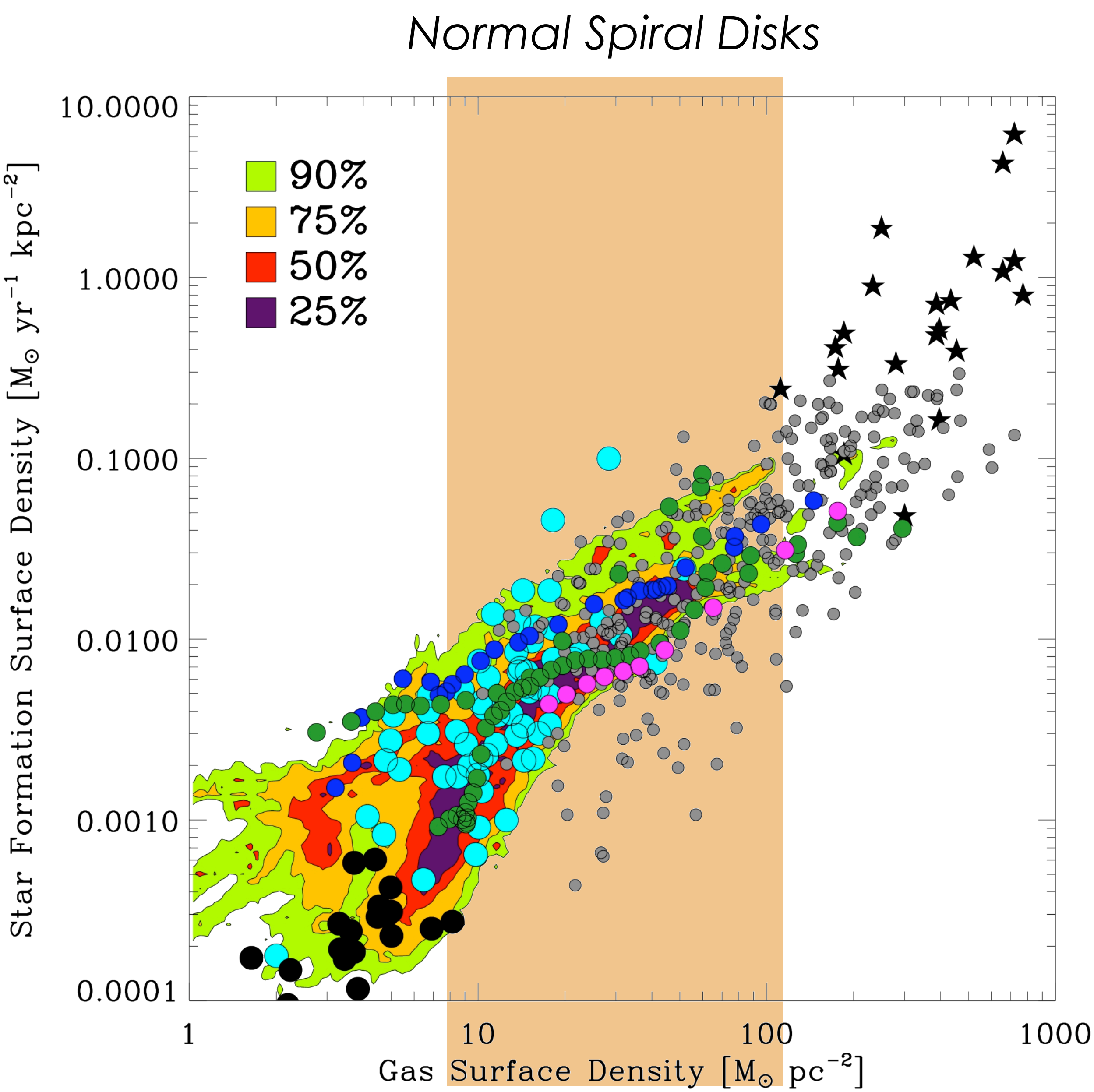
Kennicutt (1998) spirals and ★bursts; Wong & Blitz (2002); Schuster et al. (2007)
Wyder et al. (2007); Kennicutt et al. (2007); Crosthwaite & Turner (2007)

A “Star Formation Law” in 3 Parts?



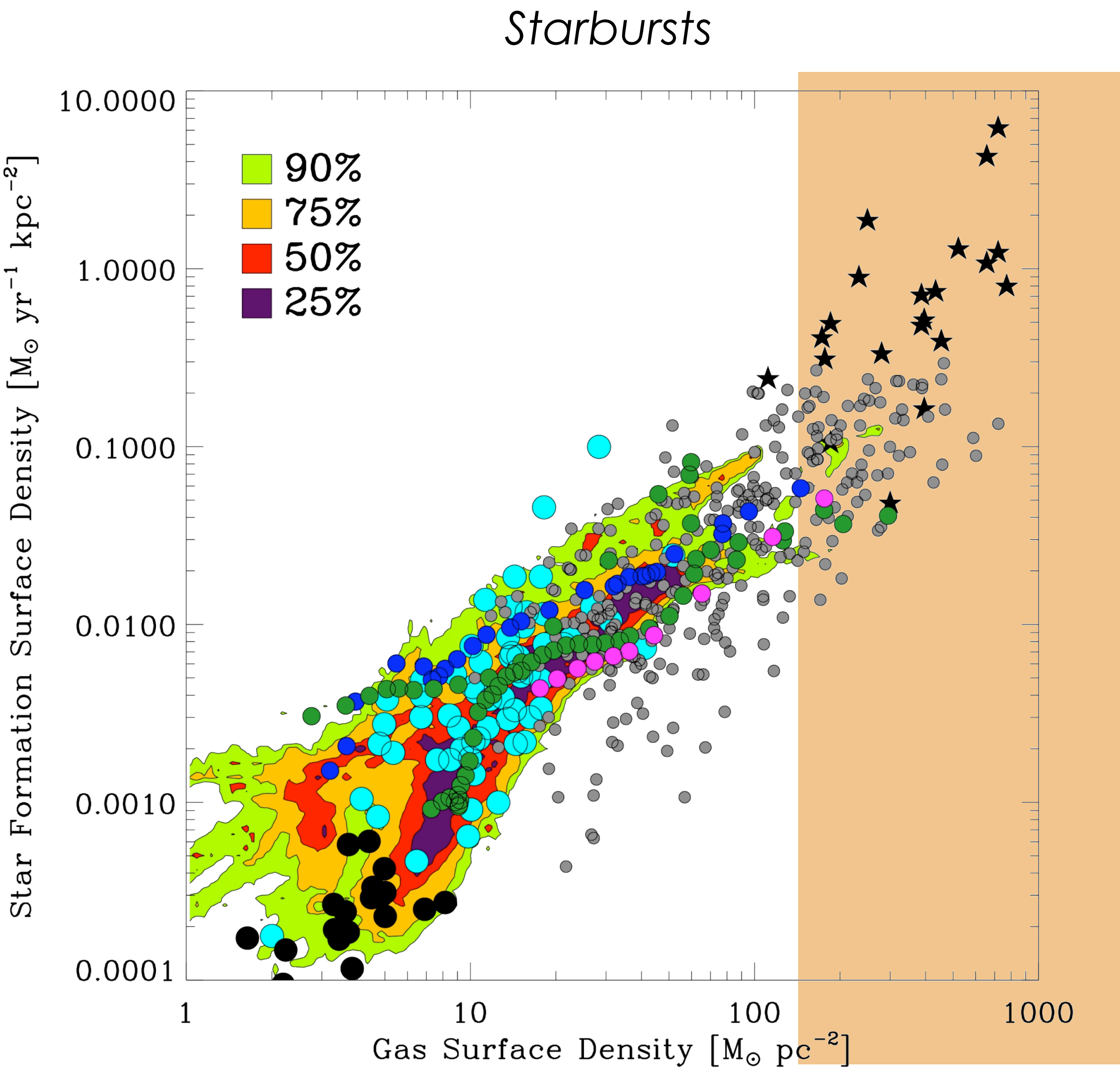
Critical quantity is the ratio of H2 to HI; below Kennicutt-Schmidt law

A "Star Formation Law" in 3 Parts?



ISM is mostly H_2; SFE(H_2) sets the star formation rate

A “Star Formation Law” in 3 Parts?

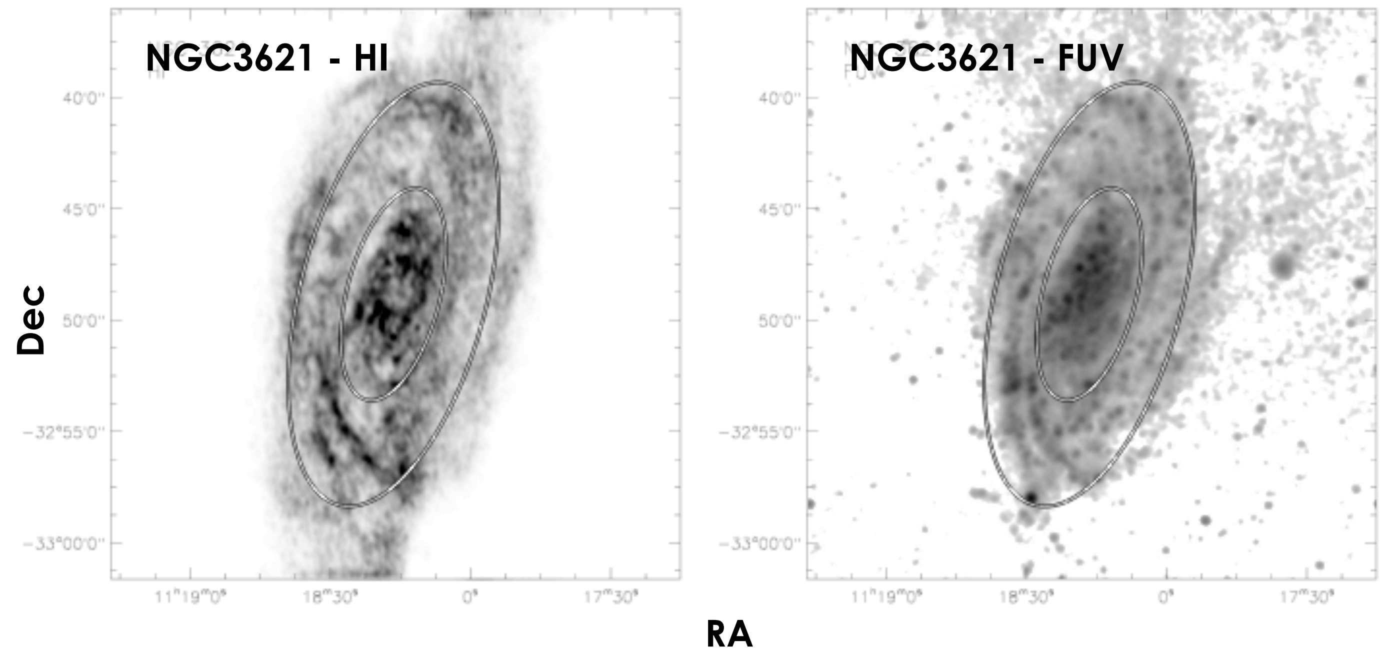


Good evidence of nonlinearity: e.g., Kennicutt (1998), Gao & Solomon (2004), Greve (2005) and …

… A. Leroy’s talk for an updated version including the latest HERACLES data

Work in progress …

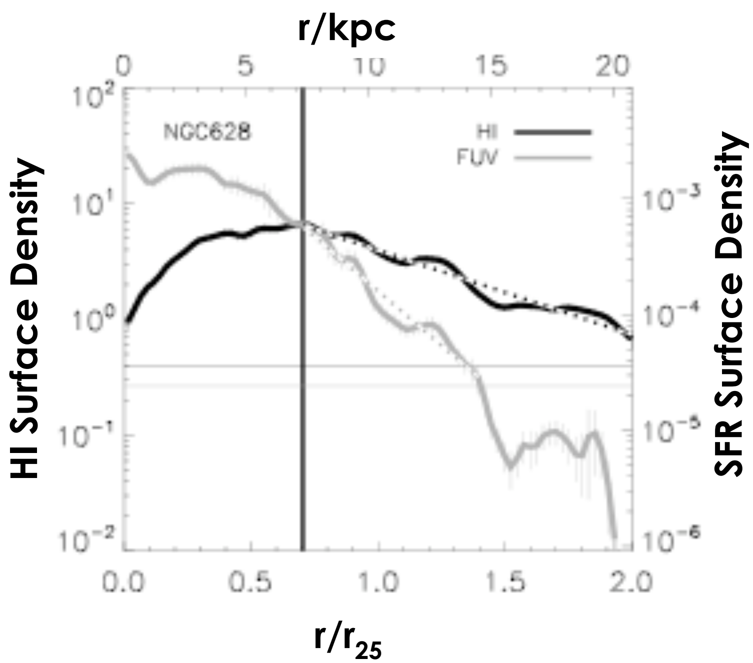
Pushing into Outer Galaxy Disks

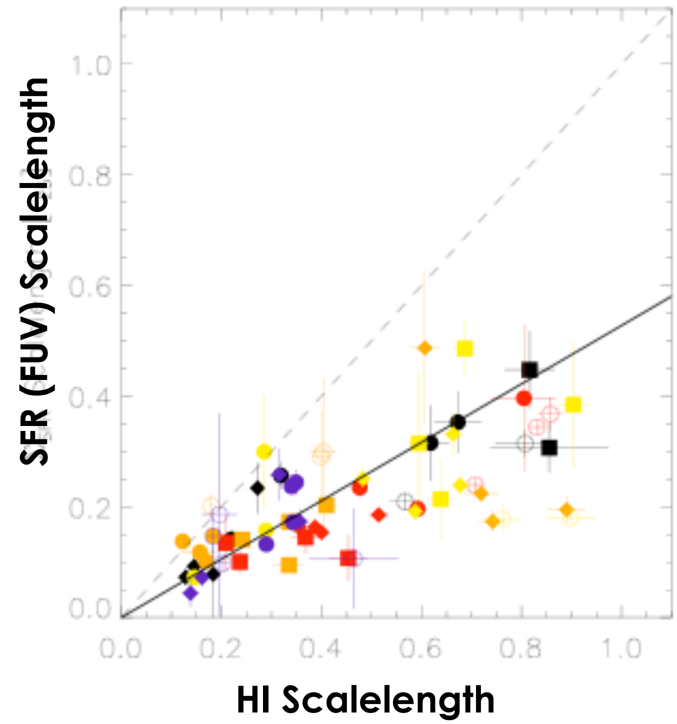


- Extend SFR-gas measurements to regime between 1 and $2*r_{25}$
- Assume $\Sigma_{gas} \sim \Sigma_{HI}$ and $\Sigma_{SFR} \sim \Sigma_{FUV}$
- Overlap of *THINGS* and the GALEX NGS: 25 galaxies

Work in progress ...

Outer Disk Scalelengths ...

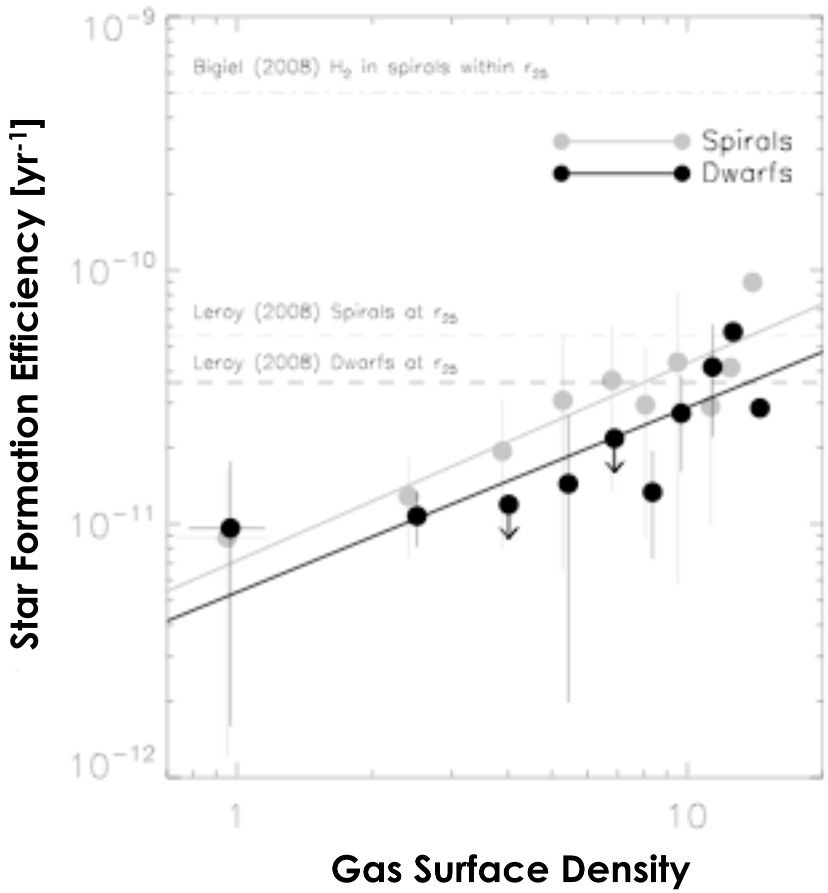




- Fit exponentials to outer parts of radial profiles to characterize the radial decline of HI and FUV emission across the outer disks

- Is the diminishing gas supply at large radii responsible for the declining SFR? HI Scalelengths are twice as large as FUV Scalelengths on average → Other (radially varying) processes must be important

… and Star Formation Efficiencies

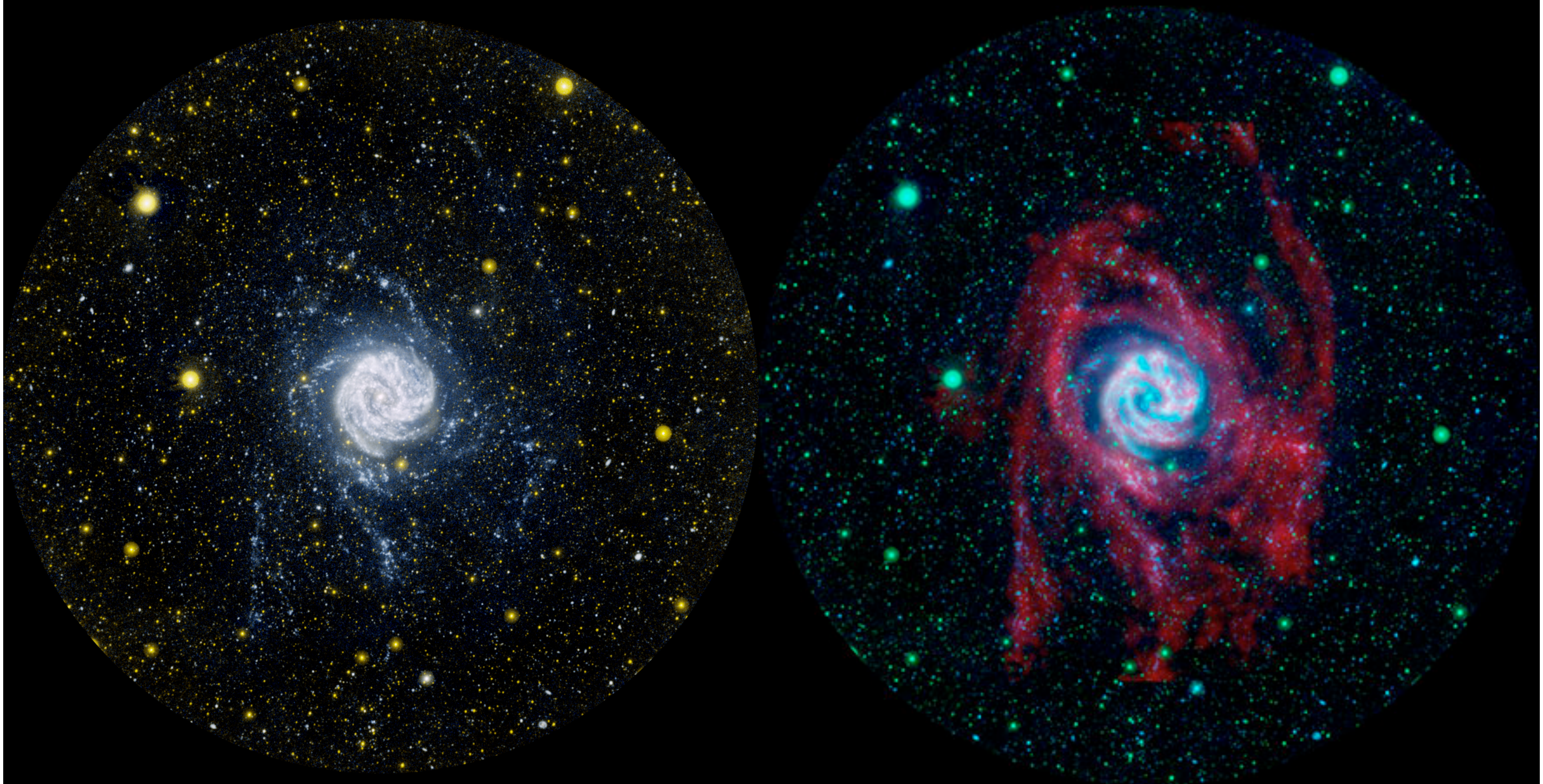


- SFE is a smooth function of Σ_{HI}

- SFE/τ_{dep} at low Σ_{HI} similar in spirals and dwarfs (and also compared to measurements in LSB galaxies; Wyder et al. 2008) → suggests that similar processes maybe responsible for setting the SFE

Work in progress …

Pushing into the Far Outer Disks…



Summary

• We use new data from (THINGS, HERACLES, SINGS and GALEX NGS) to assess the star formation law at sub-kpc resolution **pixel-by-pixel** in nearby galaxies

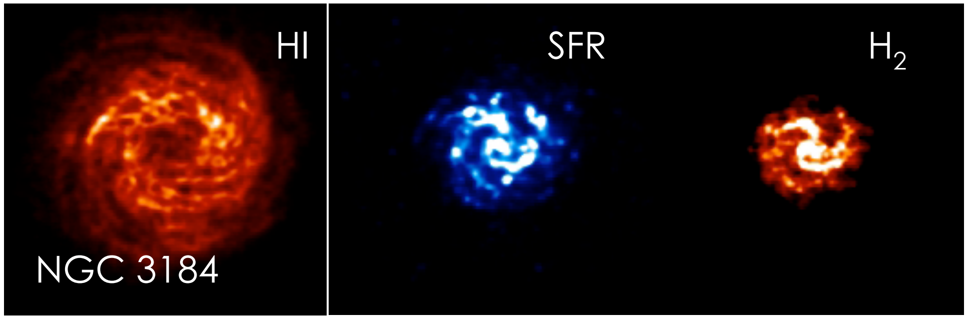
• We find a **molecular gas** Schmidt-type power law ($\Sigma_{SFR} = A \bullet \Sigma_{gas}^{N}$) relationship with a power-law index N=1.0 ± 0.2. This implies a **constant star forming efficiency** with an average H_2 gas depletion time of **~ $2*10^9$ yrs**

• To the contrary, in the **HI-dominated regime** there is no correlation between Σ_{SFR} and Σ_{gas}, i.e. Σ_{SFR} **cannot** be predicted with any accuracy from Σ_{gas} alone. There is a clear **radial gradient of the SFE and the H_2/HI ratio**

• The **saturation of Σ_{HI}** at ~9 $M_{\odot}$ pc^{-2} holds for both, spirals and dwarfs

• The decline of the SFE continues into the far outer disks of the spirals and dwarfs; the outer disk SFEs resemble those from other HI dominated environments like LSB galaxies

• The decreasing HI column alone is not enough to explain the declining SFE at large radii



The End